



The Laser Cooling and Atomic Physics (LCAP) Program at JPL

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The research described in this paper was carried out by the Jet Propulsion Laboratory,
California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

*Quest 1:
To Discover and Explore
Fundamental Physical
Laws Governing Matter,
Space, and Time*

*Quest 2:
To Discover and Understand
Organizing Principles of Nature
from which Structure and
Complexity Emerge*

In Pursuing our Quests we will:

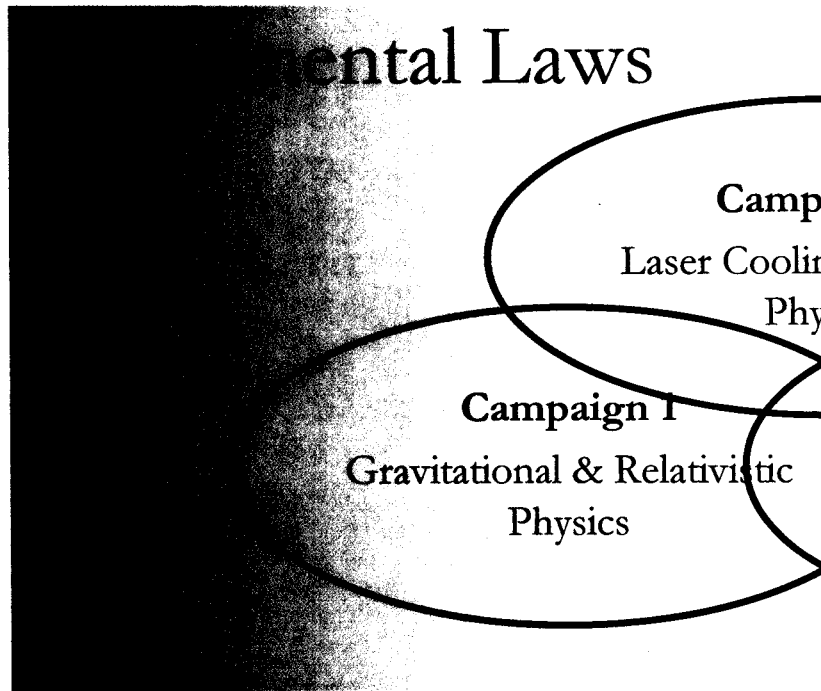
*Fulfill the Innate Human
Desire to Understand our
Place in the Universe*

and

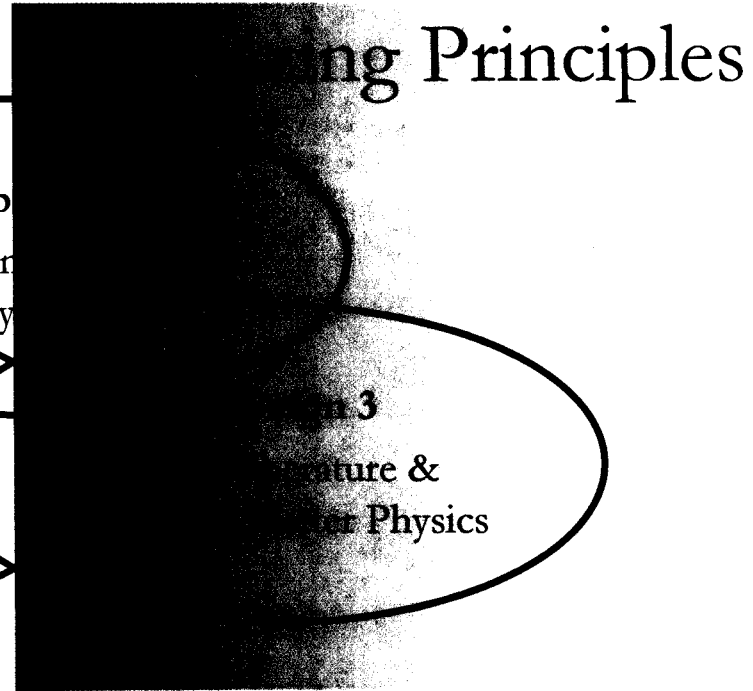
*Build the Foundation for
Tomorrow's Breakthrough
Technologies*

NASA Microgravity Research Division Fundamental Physics Roadmap

Quest 1:



Quest 2:



Laser Cooling and Atomic Physics

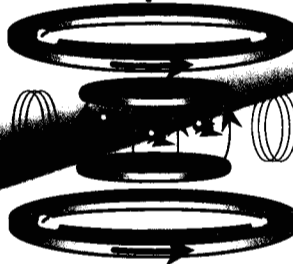
Using the space environment to investigate ...

Laser-Cooled Atomic Clocks



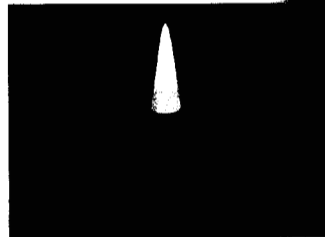
... if all clocks keep the same time or if our description of nature's forces is incomplete.

Electron-Dipole Moment



... if the electron has a dipole moment. Depending on the value, the standard model of particles and fields may have to be modified.

Bose-Einstein Condensation



... if an enhanced understanding of atomic interactions can be achieved in space.

Matter Wave Gyro



... if space can be used to establish stringent bounds on fundamental laws and forces of nature

Atom Laser



... if we can build improved atom lasers in microgravity.

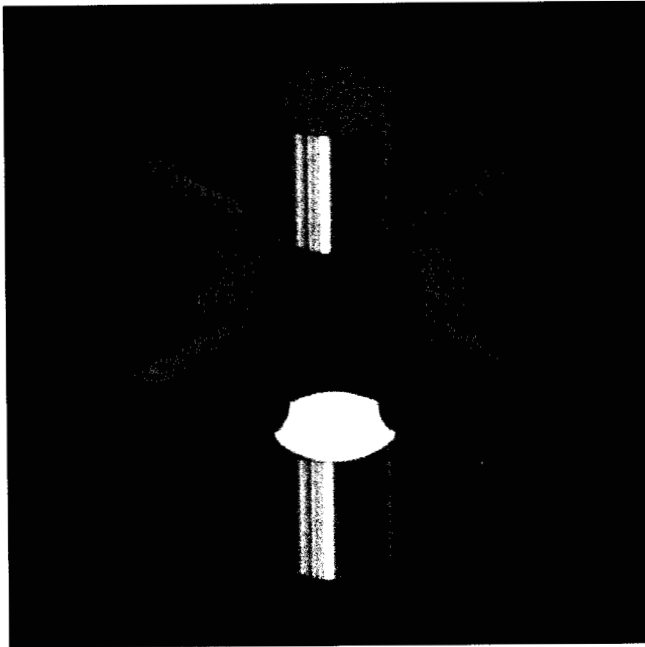
2000

2015

Future

Campaign 2: Laser Cooling and Atomic Physics

Flight experiments: Laser-cooled atomic clocks



Technology

- Magneto Optical Trap (MOT)
- Diode lasers suitable for Cs and Rb
- High-stability microwave link
- High-stability optical link
- Optical components
- Non-magnetic high-speed shutters

Science Objectives

- To perform measurement of the *Cesium clock* stability and improve the realization of the second, the unit of time, with 10^{-16} accuracy.
- To perform measurement of the collision shift of the *Rubidium clock* and demonstrate an accuracy of 10^{-17}
- To measure the gravitational red-shift by comparing clock frequency to ground-based clocks

Mission Description

- Rack mounted aboard the International Space Station or as attached payload
- Multi-frequency high stability microwave link.
- Optical link for time transfer

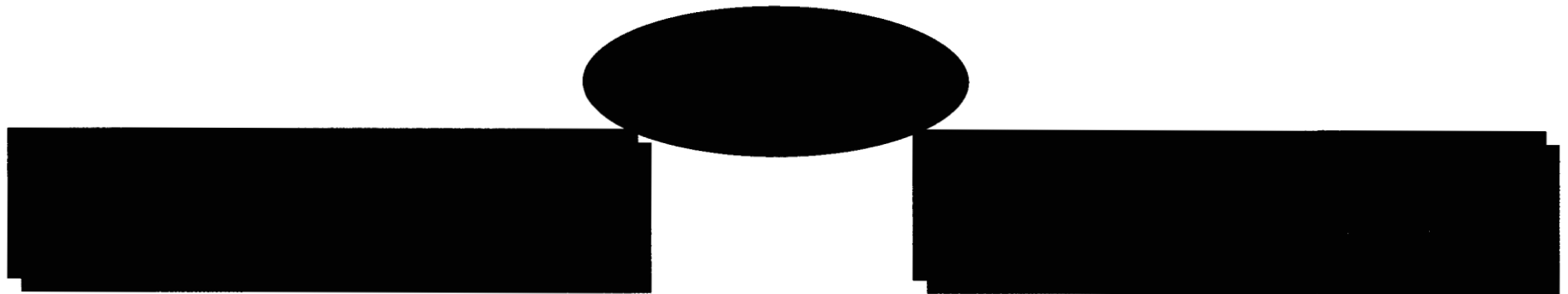
Measurement Strategy

- Compare with the ground clock using the microwave link and high resolution electronics
- Average the clock data over many orbits
- Transfer precision time to standard laboratories

Objectives of LCAP

To provide answers to fundamental open questions in physics by combining the power of laser cooling and atomic physics with the microgravity environment of space.

LCAP is the “Bridge” discipline



Atoms are quantum systems which display complexity and can be studied from first principles. LCAP is the natural bridge between Fundamental Interactions, and Complexity, and plays the interface role between the quantum and the classical worlds.

Selection of LCAP Experiments

- Selection is made through NRA process
 - Competitive, with an independent peer-review panel
- Flight definition experiments undergo Science Concept Review (SCR) and Requirement Definition Review (RDR)

State of the NASA Program

Ground Investigators

D. Hheinzen	94NRA	EDM	University of Texas
R. Hulet	94 NRA	Cooled Li	Rice University
W. Nagourney	94 NRA	Ion Clock	University of Washington
K. Gibble	94NRA	Rb Atom Clock	Yale University
M. Kasevich	96NRA	Atom Interferometry	Yale University
W. Phillips	96NRA	BEC	NIST-Gaithersburg
W. Ketterle	96NRA	BEC	MIT
J. Ho	96NRA	BEC-Theory	Ohio State University
J. Javanainen	96NRA	BEC-Theory	University of Connecticut
J. Hall	96NRA	FP tests w/clocks	University of Colorado
R. Walsworth	96NRA	Cryo hydrogen maser	SAO

Flight Investigators

K. Gibble	96NRA	Rb Clock	Yale University
D. Sullivan	96 NRA	Cs Clock	NIST-Boulder

Overview of LCAP Flight Projects

PARCS (Primary Atomic Reference Clock in Space)

Principle Investigators: D. Sullivan (NIST), N. Ashby (U. Colo.)

Development of a laser cooled and trapped **Cesium** clock for the realization of the unit of time, to operate continuously for at least 30 days. Use of orbiting clock for relativity experiments and global precise frequency distribution.

RACE (Rubidium Atomic Clock Experiment)

Principle Investigator: K. Gibble (Yale)

Development of a laser cooled and trapped **Rubidium** clock for ultrahigh accuracy (exceeding a part in 10^{16}), to operate continuously for at least 30 days. Use of clock for relativity experiments and cold collision studies.

Flight Project Collaborators

PARCS

D. Colorado

Neil Ashby (PI)

Harvard-Smithsonian

E. Vessot

Politecnico de Torino

A. Ton-Marchi

JPL:

W. M. Klipstein

J. Kohel

L. Maleki

D. J. Seidel

R. J. Thompson

RACE

Yale

Kurt Goble (PI)

JPL:

W. M. Klipstein

J. Kohel

L. Maleki

D. J. Seidel

R. J. Thompson

Clocks are crucial to test of fundamental theories

- Gravitational physics and tests of relativity
- Test of certain string theories by searching for time variation of fine structure constant
- Test of fundamental symmetries such as CP violations (edm)

Clocks are a very fast means to achieve science payoffs

- Developments in fundamental physics advance clock performance--advanced clocks enable new science and technology capabilities
- Many areas of technology (navigation, GPS, timing and time transfer) directly benefit from high performance and advanced clocks

Importance of clocks to NASA and HEDS

- Clocks are fundamental to spacecraft navigation
 - Advanced clocks enable autonomous spacecraft
 - “GPS-like” navigation systems can support Mars missions with multiple rovers, astronauts, and sensors

PARCS as a “bridge” experiment

- Realization of an atomic clock based on laser cooling in microgravity
 - ultra-high accuracy
- *Clock* test of the Equivalence Principle
 - Search for new physics beyond the standard model
- PARCS is a pathfinder experiment for all future LCAP flight experiments

Laser Manipulation of Atoms

- **Laser cooling:** 3-D optical molasses: Collect 10^8 atoms in approximately 1 second. Cool to below 10 microKelvin
- **Launching cold atoms:** Moving-frame optical molasses
Frequency shift of counter-propagating beams results in a moving rest frame for cold atoms. Can easily vary launch velocity by adjusting laser frequency difference.

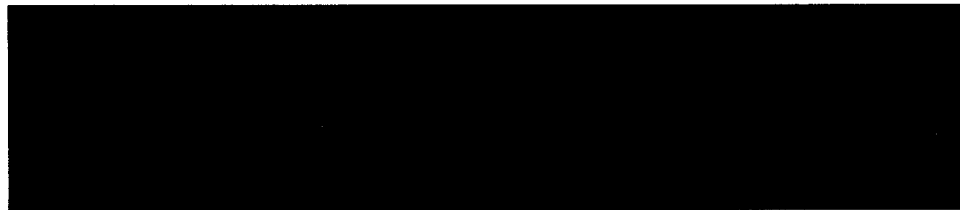
Principles of laser cooling & trapping

Absorption or emission of laser radiation can modify an atom's ...

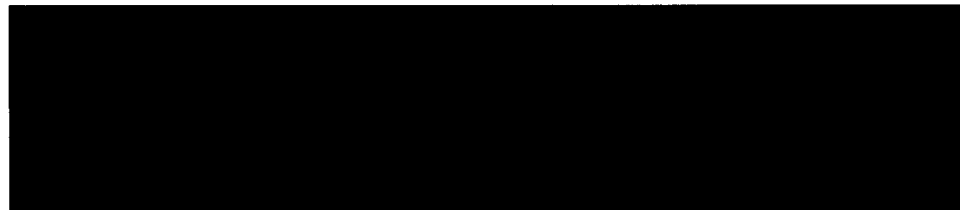
- **internal energy structure** (e.g., electronic state)
 - photon energy $\Delta E = h\nu$
- **external energy structure** (e.g., kinetic energy)
 - photon momentum $p = h\hbar k$
 - absorption rate depends on atom's velocity (Doppler effect) \Rightarrow **cooling force**
 - absorption rate also depends on external magnetic field (Zeeman effect) \Rightarrow **trapping force**

Why Microgravity?

- Heisenberg's Uncertainty Principle states that our ability to measure an energy is limited by the amount of observation time: $\Delta E \cdot \Delta t \leq h/2\pi$ (ΔE is the uncertainty in the energy measurement; Δt is the observation time).
- On earth, the observation time is limited by gravity. The best measurements are made by tossing a cold sample of atoms upwards and waiting for them to fall back down, giving roughly a 1 s observation time. In space, achieving 5–10 s observation times is possible.



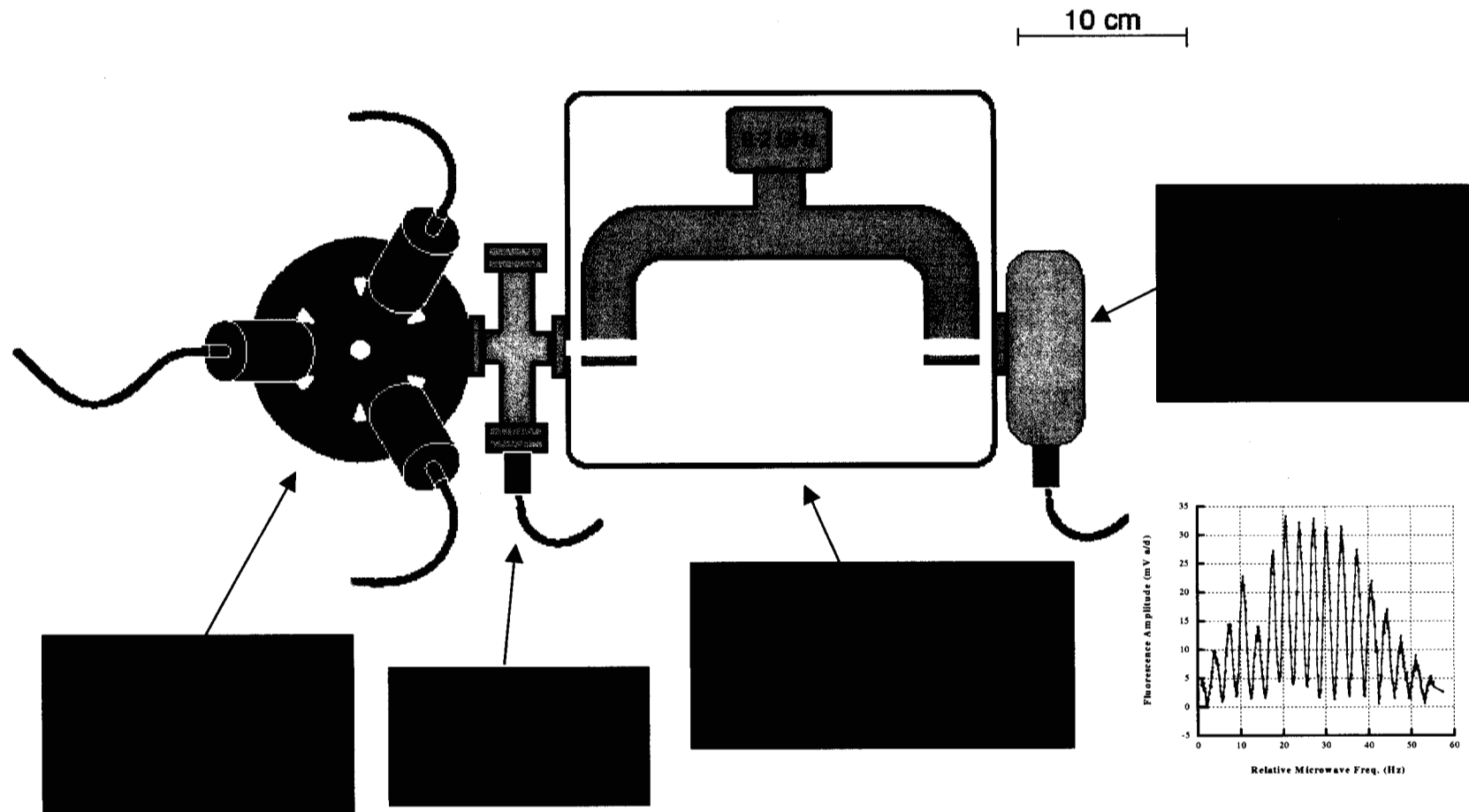
Weak gravity

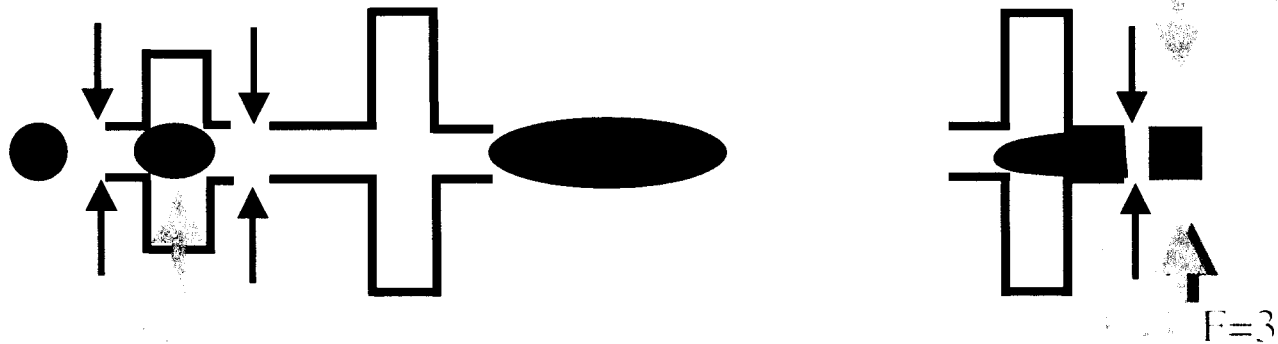


Micro-gravity

For long interaction times, quasi-steady accelerations must be less than 100 μg .

Space Clocks 101





Collect: $N_0 = 8 \times 10^7$ cold atoms/ball

Launch: $N_{m=0} = 9 \times 10^6$ in $m = 0$ at 2 Hz

Detect: $N_D = 1.5 \times 10^4$

Ramsey time: $T_R = 5$ s

Cycle time: $T_c = 15$ s

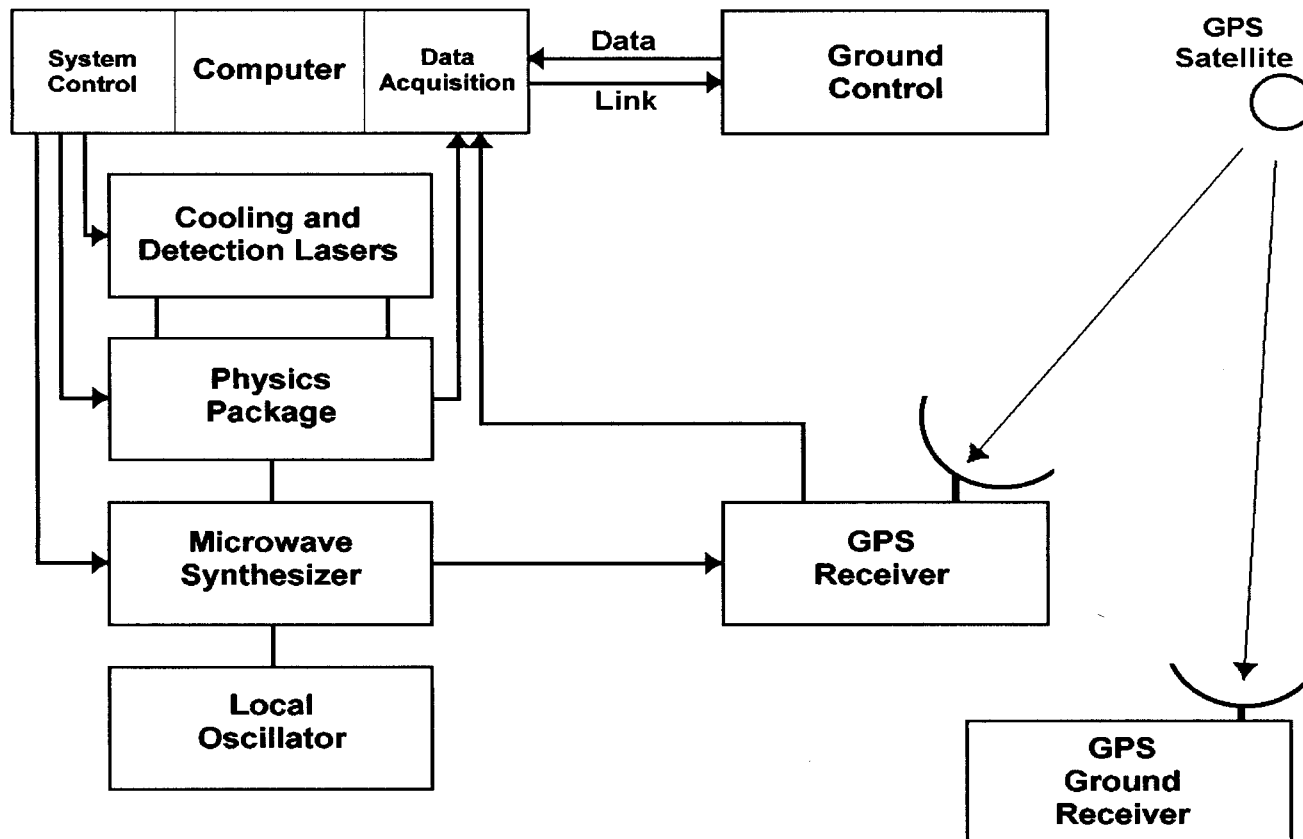
$$\Rightarrow \sigma_y(\tau) = 1.6 \times 10^{-14} \tau^{-1/2}$$

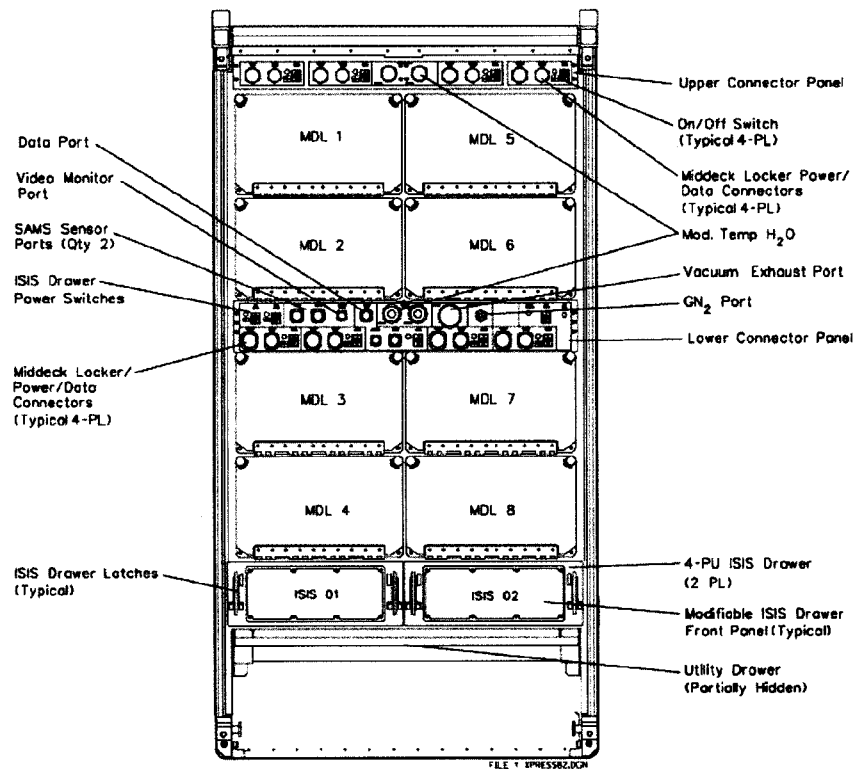
Source “brightness” achieved so far:

- $N_0 \sim 2 \times 10^8$ (in 1 s) in vapor cell molasses (Ch. Salomon, Paris)
- $N_0 \sim 5 \times 10^7$ (in 1 s) in small beam filled molasses (NIST Fountain)

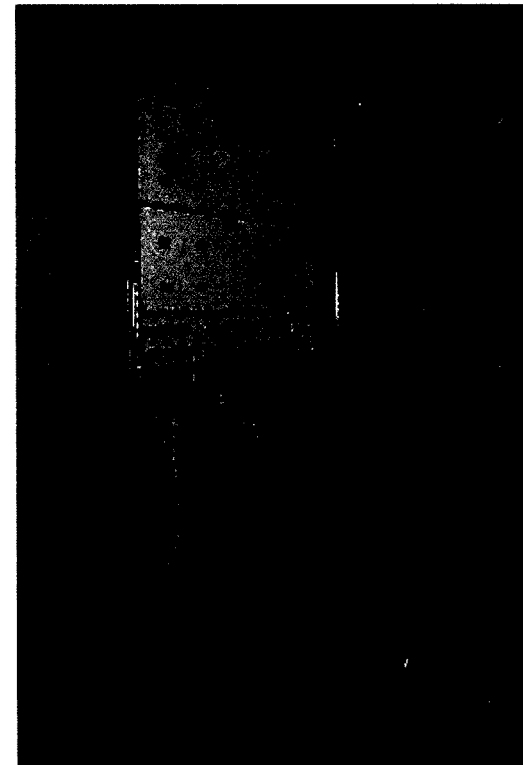
PARCS

Block Diagram of Experiment





NOTE: SAMS interface available in ARIS Rack only.



EXPRESS Rack Details (non-standard configuration)

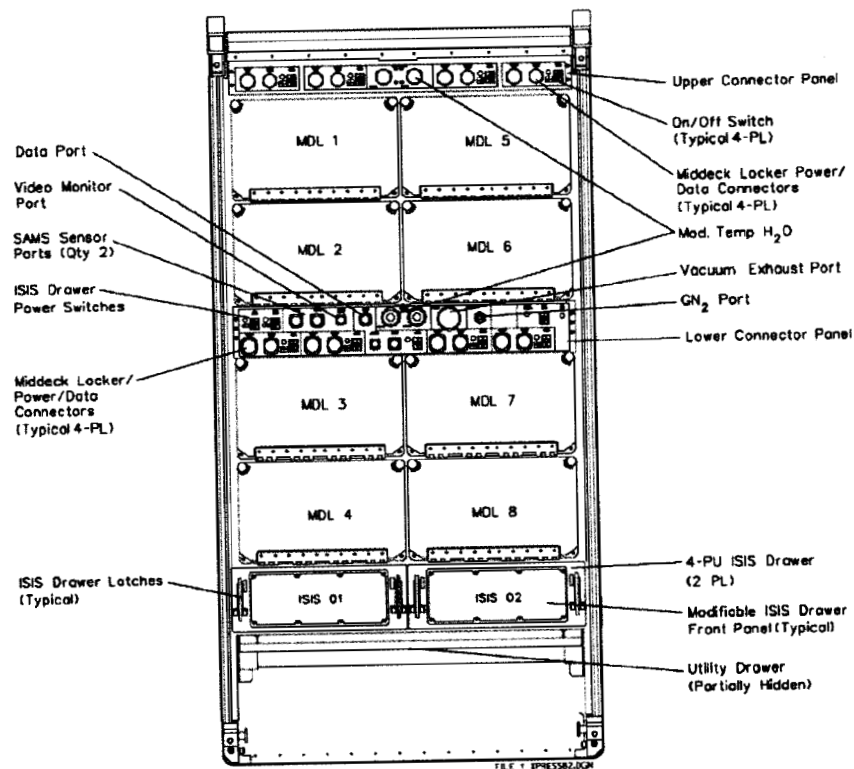
- Incorporating Active Rack Isolation System (ARIS)
- Power: ≤ 500 watts/MLE, up to 3kW for entire Express Rack. (28V DC)

Transporting Experiment to ISS

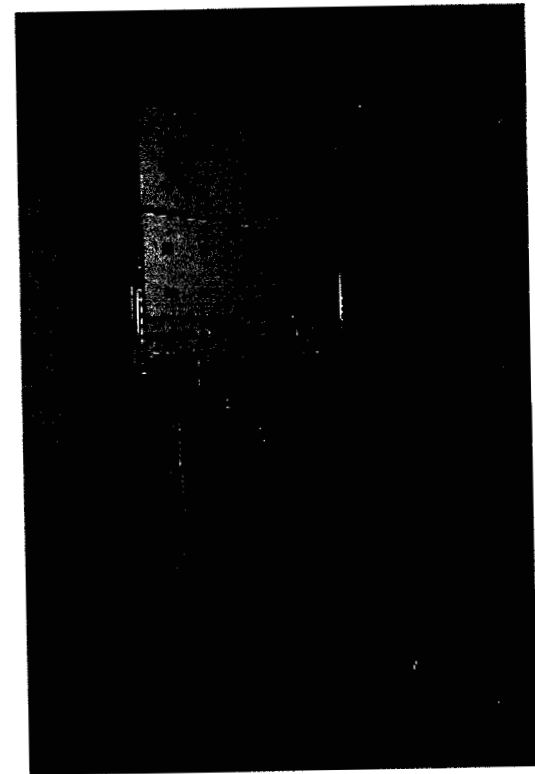
- Express transportation rack (accommodates at least six contiguous middeck lockers)
- Allows a maximum of 432 lbs for full complement of middeck lockers.

References

- SSP 52000-PAH-ERP (11/24/97); SSP 52000-IDD-ERP (5/27/98); S683-34512, Rev B



NOTE: SAMS interface available in ARIS Rack only.



EXPRESS Rack Details (non-standard configuration)

- Incorporating Active Rack Isolation System (ARIS)
- Quad MDL Internal Dimensions: w 35.7" × h 20.9" × d 20.32" (907 mm × 531 mm × 516 mm)
- Power: ≤ 500 watts/MLE, up to 3kW for entire Express Rack. (28V DC)

Transporting Experiment to ISS

- Express transportation rack (accommodates at least six contiguous middeck lockers)
- Allows a maximum of 432 lbs for full complement of middeck lockers.

References

- SSP 52000-PAH-ERP (11/24/97); SSP 52000-IDD-ERP (5/27/98); S683-34512, Rev B

JEM external facility:

- Exposed “porch” attached to Japanese Experimental Module (JEM) with slots for ten payloads
- Vibration environment measured, but no vibration isolation provided
- 3 KW power available
- Possible proximity to the superconducting Microwave Oscillator (SUMO)



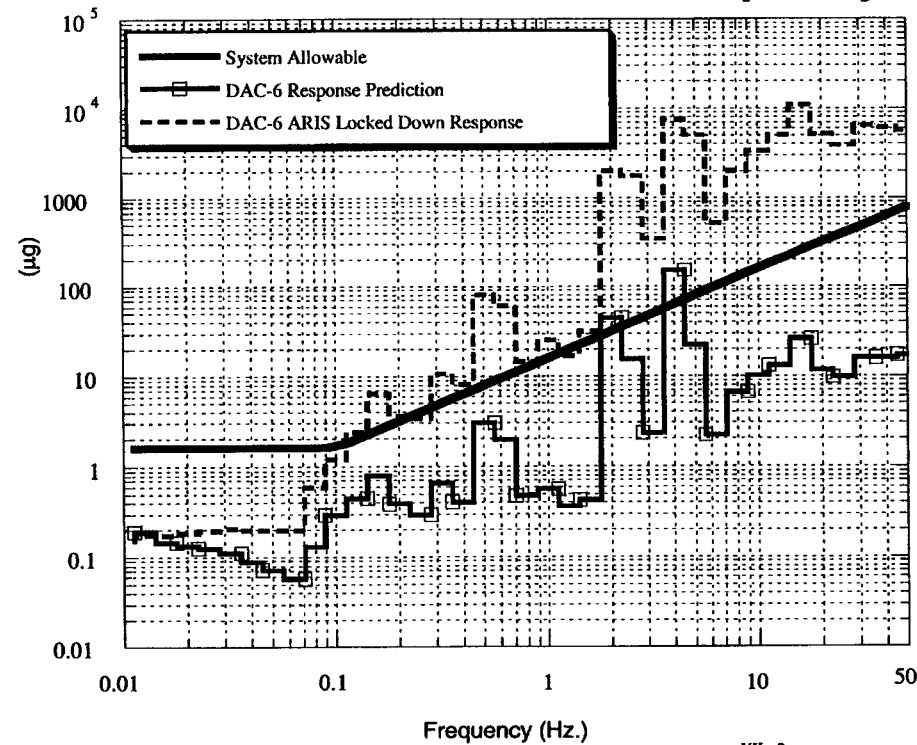
ISS Acceleration Environment Predictions

Microgravity
Environment
Interpretation
Tutorial

ISS Acceleration Environment Predictions



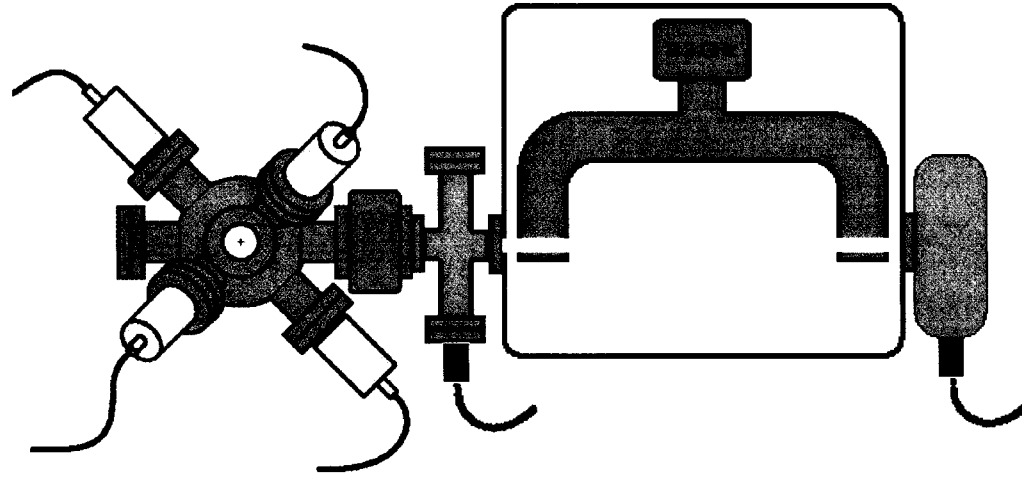
ARIS Locked Down - Low Frequency



DAC #6
6/98

Data from Boeing

Space Clock Challenges



Laser Cooled Atom Source

- Lasers
- Optical frequency control
- Optical fibers
- Fluorescence detection
- Vacuum chamber
- Computer control
- Electronics
- Magnetic field control
- Cesium atom source

Clock Package

- Microwave electronics
- Local oscillator
- Synthesizer
- Cavity
- More magnetic field control
- Thermal control
- Light baffling/shutters
- Vacuum requirements
- Measurement system

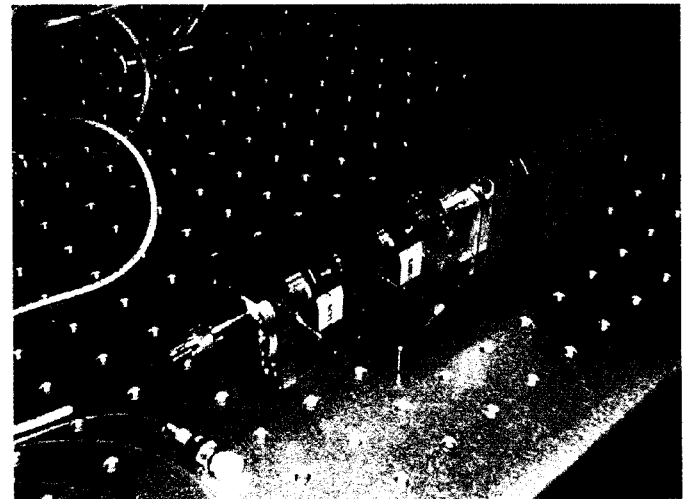
Laser System Design

Diode laser advantages

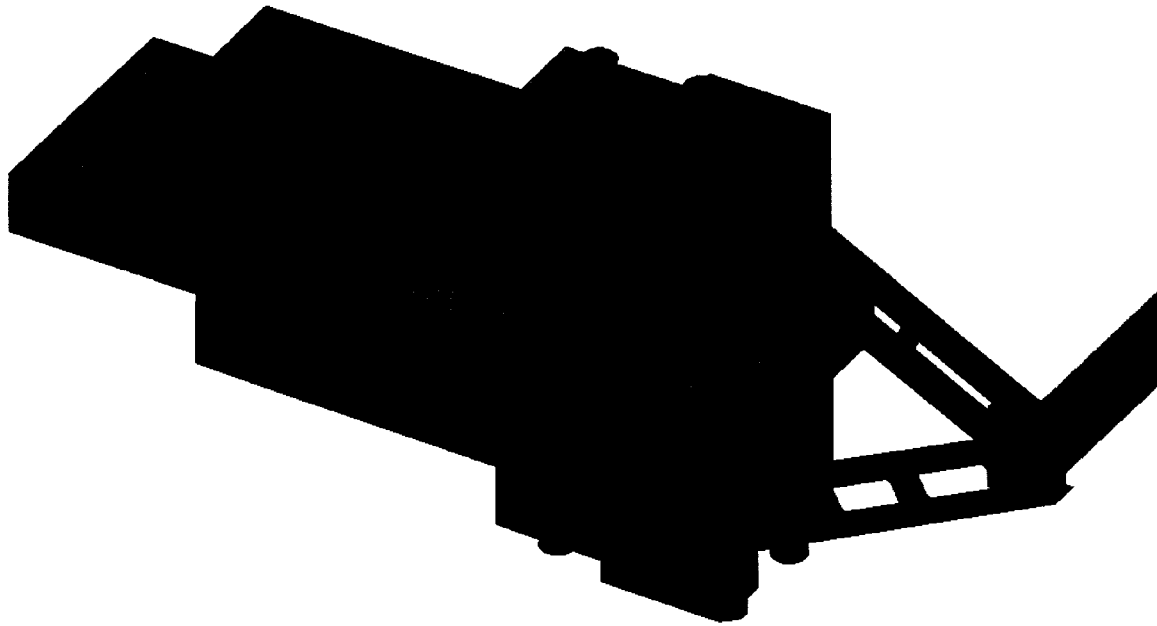
- Compact and lightweight
- High electrical efficiency
- High power, narrow linewidths

Baseline design

- Master laser (linewidth ~ 1 MHz)
- Injection-locked slave lasers (2×250 mW)
- Optical fibers for beam delivery
- Acousto-optical modulators for frequency control



Non-Magnetic Shutter Concept



High performance shutters are required by both RACE and PARCS to achieve optimal performance. Requirements include:

- High reliability (1 year operation at 10Hz w/o failure)
- Fast (< 1 ms time from 100% closed to 90% open)
- Extremely non-magnetic ($< 1 \mu\text{G}$ stray field)
- Ultra-high vacuum compatible ($< 10^{-13}$ atmosphere)
- Relatively large aperture (> 1 cm)
- Cannot disturb microgravity environment

Space Qualification of Components

Shuttle requirements:

- Vibration testing

Freq. Range	Design/Protoflight	Flight Acceptance
20 Hz	$0.02 g^2/\text{Hz}$	$0.01 g^2/\text{Hz}$
20–70 Hz	+3 dB/Octave	+3 dB/Octave
70–1000 Hz	$0.08 g^2/\text{Hz}$	$0.04 g^2/\text{Hz}$
1000–2000 Hz	–6 dB/Octave	–6 dB/Octave
2000 Hz	$0.02 g^2/\text{Hz}$	$0.01 g^2/\text{Hz}$
overall	$10.8 g_{\text{rms}}$	$7.6 g_{\text{rms}}$

Duration: *Design:* 2 min; *PF & FA:* 1 min in each of 3 axes

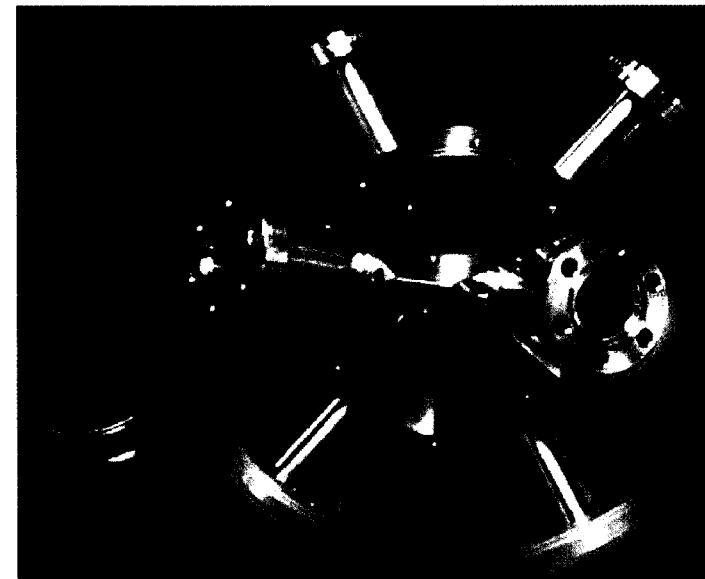
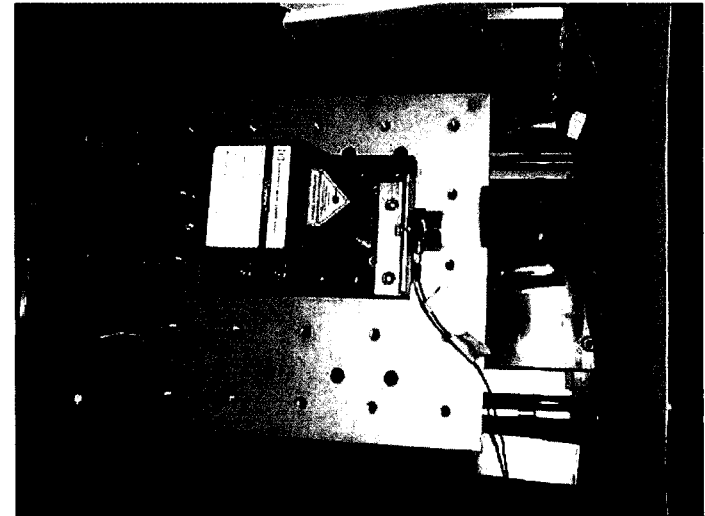
- Thermal testing

Must survive over a -5 to 50°C range

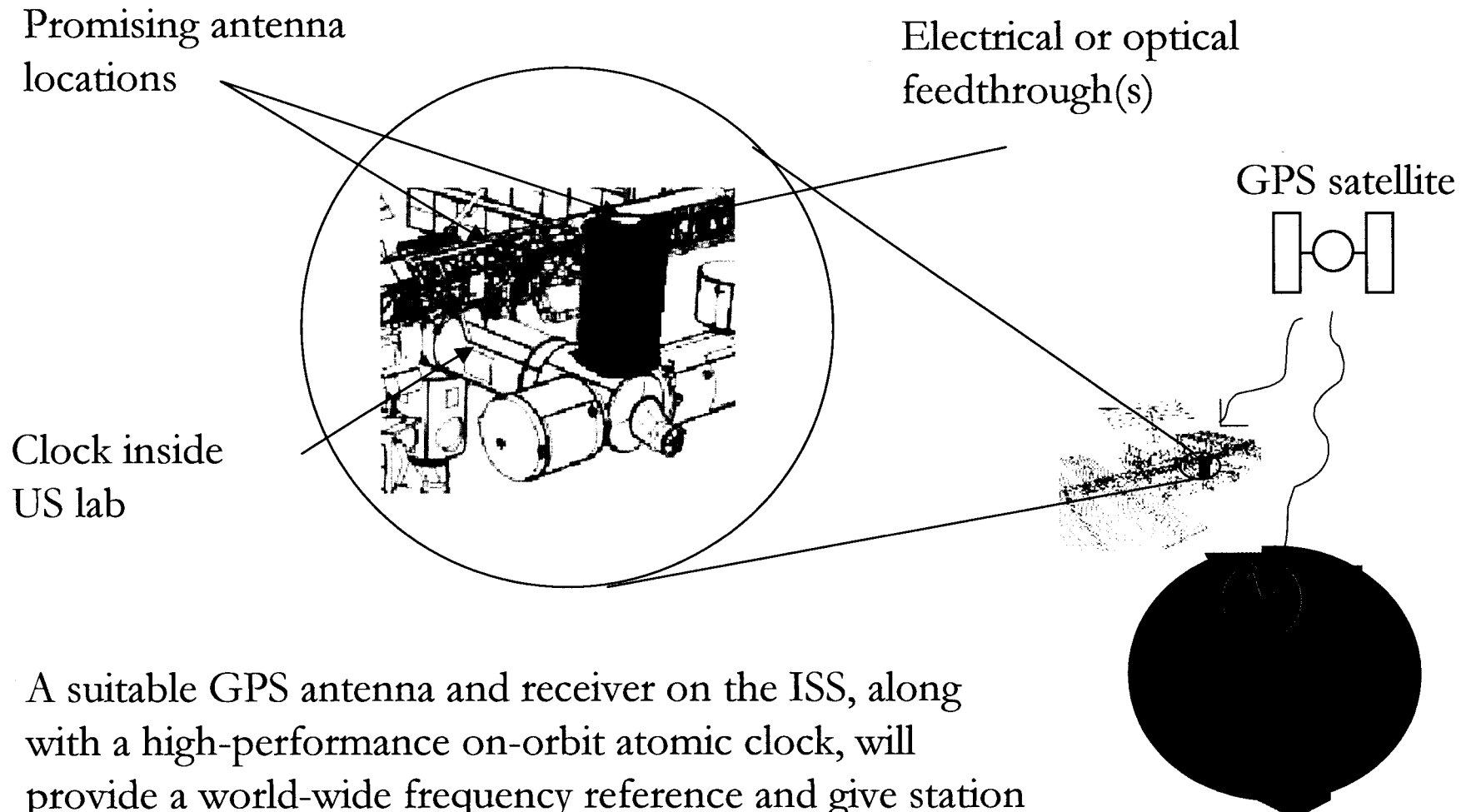
Above: New Focus Vortex™ laser on vibration test bed at JPL.

Left: Titanium vacuum chamber and welded window assembly for laser-cooled Cs source.

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Time and Position Metrology from ISS using GPS Carrier Phase



A suitable GPS antenna and receiver on the ISS, along with a high-performance on-orbit atomic clock, will provide a world-wide frequency reference and give station users precise position information

PARCS Time Transfer

Requirements to meet science objectives

- 100 ps time transfer stability
 - Position and velocity determination: $\Delta x < 10$ cm, $\Delta v < 1$ cm/s
- ⇒ Use **GPS carrier phase technique**

Technical issues

- Need external antennae
- High quality rf link
- Multipath interference
- Visibility of GPS satellites



GPS Carrier Phase

Hardware requirements

- GPS choke-ring dual-frequency receive-only antenna on ISS exterior (zenith pointing), with minimum π steradians of clear above-horizon viewing and ~ -70 dBm interference at 1.5 and 1.7 GHz. Amplifier and receiver may be collocated with antenna.
- Dedicated analog RF link between the US lab (internal) and the GPS Antenna (external). Link could be similar to the I/F link between the US lab and the Ku-Band Antenna, or a single-mode fiber optic link. Fiber option would require 12 W power delivery to the antenna. Multiple feedthroughs would allow for multiple antennae.
- Low-phase-noise cable from high-stability atomic clock and receiver on orbit to feedthrough (e.g., Andrew Corp. Helias cable) or single-mode optical fiber.

Benefits to ISS users and public

- Precise position and velocity determination will benefit experiments which need to point antennae/telescopes and allow on-orbit scientific measurements.
- Provides common international frequency reference for communications and science on the ground (10^{-16} accuracy).

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LCAP Timeline

